RESEARCHES UPON THE GENERAL PHYSIOLOGY OF NERVE AND MUSCLE.

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No. 1.

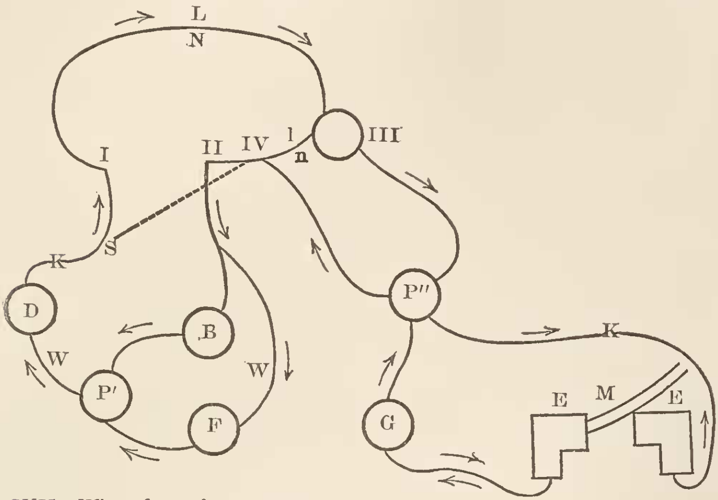
Electrical currents and Electro-motive force of Muscle and Nerve in frog. Whatever view may be entertained as to the nature of the electrical currents present in injured muscle or nerve, whether the same be regarded as pre-existing in the uninjured condition, or as being developed through injury, there can be no difference of opinion as to the fact that such currents exist, at least in the injured condition. In as much, however, as so far known to the authors of this communication, all researches hitherto undertaken with the object of demonstrating the presence of electrical currents in muscle and nerve, and of more particularly determining the electro-motive force of the same, have been made by Prof. Du Bois Reymond it does not appear superfluous to bring before the attention of the Academy the results of some recent investigations made by the authors in the Laboratory of Jefferson Medical College upon large specimens of our our common frog, *Rana Catesbiana.* That the presence of electrical currents in nerve and muscle should have long escaped the notice of physiologists was doubtless due, not only to the imperfect forms of galvanometers formerly in use, but also to the fact of electrical currents being developed whenever two electrodes were placed in contact with organic tissues. With the construction of delicate galvanomters, like those of Wiedemann, and of non-polarizable electrodes, that is of electrodes that will convey or divert an electrical current present in a muscle or nerve to a galvanometer, without generating one, it became possible to demonstrate without cavil that injured muscle and nerve are seats of electro-motive force. The instruments made use of in obtaining the results tabulated below, were of the convenient form devised for this purpose by Prof. Du Bois Reymond,[1] to whom this branch of science is so much indebted, and consisted of a Wiedemann galvanometer with telescope and scale, a round compensator, mercurial keys and whippe and non-polarizable diverting cylinders and diverting vessels[2], the latter or non-polarizable electrodes being always

[1] Gesammelte Abhandlungen, Leipzig, 1875, Band I.

[2] A description of these instruments will be found in Chapman's Physiology 1887, Chap. XXXVIII.

applied to the equator and transverse section of the muscle and nerve respectively. The methods made use of by the authors in determining the electro-motive force of the gastrocnemius muscle and sciatic nerve of the frog as given in the synopsis below is essentially that of

SCHEME OF DETERMINATION OF ELECTRO-MOTIVE FORCE WITH ROUND COMPENSATOR.



IVII	Wire of round compensator.
N	Number of its divisions 1000.
L	Resistance offered by same.
S	Switcher.
K	Key.
D	Daniell Element.
W	Resistance offered by D IVII B P′ D and by IVII F P′ D.
P′	Whippe.
B	Coils.
F	Coils.
P″	Commutator.
G	Galvanometer.
E	Electrodes.
M	Muscle or Nerve.
K	Key.
III	Wheel.
l	Fractional portion of wire of compensator.
n	Number of the division necessary to compensate.

Poggendorff with the difference that the round compensator was used instead of the long rheocord. This method[1] consists essentially in

1 Du Bois Reymond, op. cit. S 257.
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shunting off from the circuit of a standard element, a Daniell's cell for example, whose electro-motive force is known = 1·08 Volt, an amount of current sufficient to neutralize or compensate the current deflecting the magnet, the latter due to the electro-motive force of the muscle or nerve and which is to be determined. Thus, for example, let us suppose that the electrical current diverted by the non-polarizable cylinders or electrodes, Fig. 1 (E) from the nerve or muscle (M) to the galvanometer (G) be sufficient to deflect the magnet to an extent corresponding to 267 divisions of the scale. If now the compensator be moved so that the wheel III be opposite (n) for example, part of the current from the Daniell element will return through IVII F whence it came and part through III P″ to the muscle (M) and, being in the reverse direction to that of the current from and due to the muscle, the magnet will be slowly brought back from the the 267th division of the scale to zero, the wheel III then standing at (n), or the 820th division of the wire of the compensator, the latter (N) being divided into 1000 parts. Such being the case it is evident that the electro-motive force of the muscle or X is to that compensating it, or to (l), (the amount of the compensating force depending upon the resistance offered by the fractional portion of the wire L) as the electro-motive force of the Daniell element or (E) is to the whole resistance or W+L, or more briefly:—

$$X : l : : E : W+L$$

or

$$X = \frac{l}{W+L} \times E \quad (1)$$

In as much, however, as the fractional portion of the wire (l) is to the number of its divisions or (n) as the whole wire (L) is to the number of its divisions N we shall have

$$l : n : : L : N$$

or

$$l = \frac{n\,L}{N}$$

If now this value of l be substituted in equation (1) we shall obtain

$$X = \frac{n}{N\left(1 + \frac{W}{L}\right)} \times E \quad (2)$$

and it only remains, n and N being known, to determine the ratio of W to L to obtain the value of X or the electro-motive force of the muscle as a fractional portion of E, the latter being the electro-motive force of a Daniell element. To accomplish this let the circuit M G P″ IV III P″ K M and the circuit D K I, III, IV II F P′ D, be opened and the circuit D S IV II B P′ D offering a resistance W be closed, D being put in communication with IV by the switcher S, B being a coil of wire offering the same resistance as F and brought sufficiently near the galvanometer G to slightly affect it, the intensity of the current will then be equal to the ratio of E to W or $I = \frac{E}{W}$ or if we call J the number of the divisions of the scale corresponding to the deflection of the magnet, then $J = \frac{E}{W}$ Let now D be put in communication by means of the switcher S, with I, the beginning of the wire of the compensator, that is the current D K S I III IV II B P′ D be closed and offering a resistance W+L, L being the resistance offered by the wire I II of the compensator, the intensity of the current will then be equal to the ratio of E to W+L, that is $I = \frac{E}{W+L}$ or if we call J^1 the number of divisions corresponding to the deflection of the magnet, then $J^1 = \frac{E}{W+L}$

$$\text{or } \frac{J}{J^1} = \frac{\frac{E}{W}}{\frac{E}{W+L}} = \frac{W+L}{W} \quad \text{whence} \quad W\frac{J}{J^1} = W+L \text{ or}$$

$$\frac{W}{L} = \frac{1}{\frac{J}{J^1} - 1} = \frac{J^1}{J - J^1}$$

If now this value of $\frac{W}{L}$ be substituted in equation (2) we will obtain

$$X = \frac{n}{N} \times \frac{J - J^1}{J} \times E \quad (3)$$

in which equation

X = the electro motive force of muscle.

n = the number of divisions of the graduated scale of the wire of the compensator necessary for compensation.

N = 1000; the number of divisions of the wire of the compensator.

J = Number of divisions of scale corresponding to deflection of magnet excluding the wire of the compensator.

J^1 = Number of divisions of scale corresponding to deflection of magnet including the wire of the compensator.

E = The electro motive force of the Daniell element.

Substituting the value of n and of J and J^1 obtained experimentally as described above and equation (3) becomes:—

$$X = \frac{820}{1000} \times \frac{90-81}{90} \times E$$

or

$$X = \frac{1}{12} E = 0{\cdot}0833 \text{ D.}$$

that is to say the electro motive force of the muscle or X that deflected the magnet to an extent corresponding to 267 dimensions of the scale is equal to 0·0833 of a Daniel element.

Finally it will be observed that the graduating of the compensator or the determining the amount of the fractional portion of the Daniell necessary to compensate the muscle current is accomplished immediately after compensating or before, since $\frac{J-J^1}{N\ J}$ from (3) $= \frac{1}{10000}$ of the Daniell, that is each division of the wire of the compensator at that moment switches off the $\frac{1}{10000}$th of a Daniell and as it required 820 such to compensate, $\frac{820}{10000} = \frac{1}{12}$ was the fractional portion of the Daniell element needed. It need hardly be added that in determining the electro-motive force of a nerve, we proceed in exactly the same way except that we make use of the diverting vessels as electrodes instead of diverting cylinders.

It may be mentioned incidentally that in all of the experiments performed in the above manner the telescope and scale were placed at a distance of 2·5, met (8 feet) from the galvanometer, the coils lay close up to the magnet, that the temperature of the laboratory was about 70°F. (38·9 C) the season January and February, the time of day noon. The following table gives the results synoptically arranged of 25 experiments performed upon the gastrocnemius of the frog and of 25 experiments upon the sciatic nerve of the same animal. Resuming, it will be observed that the average deflection of the magnet due to the electrical current of the muscle corresponded to 217 divisions of the scale, the electro-motive force causing the same the $\frac{1}{14}$th of a Daniell or 0·0696 D. a greater electro-motive force than that yet obtained, the same amounting according to Du Bois Reymond [1] to 0·035—0·075 D. the mean of which is 0·055D. It may be also mentioned incidentally in this connection that the electro-

[1] Op. cit. Band II, S. 243.

motive force of the semi-membranous muscle was found in several instances to amount to as much as the $\frac{1}{10}$th of a Daniell or 0·1 D. The deflection of the magnet due to the electrical current of the sciatic nerve corresponded on an average to 21 divisions of the scale, the electro-motive force giving rise to it to the $\frac{1}{50}$th of a Daniell or 0·0237 D. a result agreeing closely with that of Du Bois Reymond[1] viz:—0·022 D. In conclusion it is worthy of observation that the electro-motive of the muscle is more than three times as great as that of the nerve.

Synopsis of results of observations upon the electrical currents and electro-motive force of muscle and nerve in frog.

GASTROCNEMIUS MUSCLE.

Observation.	Magnetic Deflection.	Electro Motive Force.
1	186 div. of scale.	0·0625 D.
2	141 "	0·0666 "
3	155 "	0·0769 "
4	170 "	0·0714 "
5	190 "	0·0588 "
6	197 "	0·0666 "
7	165 "	0·0714 "
8	255 "	0·0714 "
9	217 "	0·0588 "
10	225 "	0·0588 "
11	191 "	0·0555 "
12	245 "	0·0769 "
13	225 "	0·0625 "
14	211 "	0·0769 "
15	270 "	0·0833 "
16	266 "	0·0625 "
17	216 "	0·0833 "
18	267 "	0·0833 "
19	266 "	0·0833 "
20	258 "	0·0833 "
21	207 "	0·0625 "
22	230 "	0.0588 "
23	200 "	0·0588 "
24	225 "	0·0714 "
25	260 "	0·0769 "
mean =	$\frac{5438}{25}$ = 217 div.	$\frac{1·7424}{25}$ = 0.0696 D.

[1]Op. cit. Band II, S. 250.

Sciatic Nerve.

Observation.	Magnetic Deflection.	Electro Motive Force.
1	25 div. of scale.	0·0277 D.
2	15 "	0·0212 "
3	19 "	0·0217 "
4	20 "	0·0222 "
5	30 "	0·0333 "
6	30 "	0·0333 "
7	27 "	0·0333 "
8	28 "	0·0333 "
9	19 "	0·0200 "
10	17 "	0·0208 "
11	19 "	0·0208 "
12	16 "	1·0180 "
13	17 "	0·0181 "
14	26 "	0·0256 "
15	23 "	0·0250 "
16	18 "	0·0185 "
17	19 "	0·0185 "
18	22 "	0·0185 "
19	27 "	0·0294 "
20	15 "	0·0181 "
21	18 "	0·0200 "
22	20 "	0·0250 "
23	19 "	0·0192 "
24	20 "	0·0263 "
25	24 "	0·0270 "
mean	$\frac{533}{25} = 21$	$\frac{0·5948}{25} = 0·0237$ D.